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STATIC ELECTRICITY
A LITERATURE REVIEW (U)

by

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ABSTRACT

This paper explains what static electricity is and how fibres can be modified to reduce their electrical charge. It describes the various test methods used in the study of static electricity and the research results of various authors. It cites various incidents attributed to static electricity and concludes with a static electricity safety code.

RESUMÉ

ELECTRICITE STATIQUE - UNE REVUE DE LA LITTERATURE

Ce document explique ce qu'est l'électricité statique et comment les fibres peuvent être modifiées pour réduire leur charge électrique. Il décrit les différentes méthodes de test utilisées dans l'étude de l'électricité statique et les résultats des recherches de différents auteurs. Il cite différents incidents attribués à l'électricité statique et termine avec un code de sécurité de l'électricité statique.

EXECUTIVE SUMMARY

The major concern with static electricity is its discharging in a flammable atmosphere which can explode and cause a fire. Textile materials can have their electrical resistivity decreased by the addition of antistatic finishes, imbedding conductive particles into the fibres or by adding metal fibres to the yarns. The test methods used in the studies of static electricity include measuring the static properties of materials, of clothed persons and the ignition energy of flammable gases.

Surveys have shown that there is sparse evidence for fires definitively being caused by static electricity. However, the "worst-case" philosophy has been adopted and a static electricity safety code is described, including correct grounding procedures and the wearing of anti-static clothing and footwear.

Research has shown that under laboratory conditions, sparks from textile materials can ignite flammable mixtures. However, the actual spark energy needed to ignite such mixtures can be anywhere from 3.5 to 150 times higher than published theoretical minimum values of ignition energies.

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1.0 INTRODUCTION

A new clothing system for dry/wet and dry/cold conditions is being introduced into the Canadian Forces, primarily for the Land Element. The Air Element have shown an interest in modifying the system for their groundcrew, one requirement being the minimal generation of static electricity. Since static electricity has not been addressed within the Department of National Defence for about twenty years, this review of literature was undertaken to update the Department on new fibres and finishes which decrease static charge, test methods of measuring static electricity, standard minimum acceptable levels of charges and pertinent research results.

2.0 WHAT IS STATIC ELECTRICITY?

Static electricity is most commonly generated when different materials are rubbed together. A neutral atom has enough negatively-charged electrons to balance the positively-charged protons in its nucleus. When this atom comes into contact with another atom, some of its electrons will be attracted to the other nucleus of the second atom. Some of these electrons may be carried away with the second atom when the contact is broken. The material which loses the electrons becomes positively charged, and the other material, negatively charged. Materials differ in their propensity to lose some of their electrons when in contact with another material. Textile materials may be ranked in this respect as in Table 1. Any of these materials will give up electrons and become positively charged if rubbed against another material that is lower in the table.

Table 1

Triboelectric ranking of textiles
(from Verschave and Firmin (1))

Positive

- Wool
- Nylon
- Viscose
- Cotton
- Silk
- Acetate
- Polyvinyl chloride
- Polyester
- Acrylic
- Modacrylic
- Polyethylene
- Teflon

Negative

3.0 ELECTRIFICATION AND DISCHARGE

Electrical energy is stored in materials which have a static charge. In the case of the negatively charged material, the excess electrons, because they have the same charge, repel each other. Given the opportunity, these charges will escape through any conductive medium to another material that is electrically positive or neutral (ground). The same is true of the positively charged material except that the positive charges are not mobile, being part of the nucleus of an atom. When in contact with an electrical ground, electrons flow from the ground to the positive charge. In either case, the charges flow because of the difference in electrical potential between the charged material and ground. This potential is measured in units of volts and is directly proportional to the charge on the material. The constant of proportionality, called the capacitance, depends on its size and shape. A material with a small capacitance develops a high voltage with a small amount of charge. If the charged material is not in contact with an electrical ground, but is surrounded by air, the charge cannot easily get away because electrons travel through air with difficulty. The air is said to have a high electrical resistance. The charge will leak slowly through the air to ground after charging has stopped.

The charge on the surface of the material can also apply a force on other charged objects in its vicinity. This ability to act at a distance is explained by introducing the concept of an electric field surrounding charged objects, much as a gravitational field surrounds objects with mass. Free electrons will be accelerated by the forces applied to them by the field. At high values of electric field strength, these electrons will collide with and excite the electrons of the molecules in the air, causing them to give off light when they drop down to their normal energy level. This glow, or corona, is most often seen around pointed objects where, because of geometry, the electric field is the strongest. In the days of wooden sailing ships, it was called St. Elmo's Fire when it appeared on the mast head in a thunderstorm. Sharp points can be used to reduce accumulations of charge on clothing materials. For instance, short stainless steel fibres blended into yarns have intense electric fields at their ends, allowing the charge to bleed off into the air. At still higher electric field strengths, the energy of the collisions between free electrons and air molecules can strip the electrons off the molecules causing a cascade effect that breaks down the electrical resistance of the air. The result is a spark or a series of sparks.

Textile materials which make up clothing are poor conductors of electricity when they are dry and they build up large charges which eventually discharge to a lower potential as described above. We have all seen the sparks which fly when clothing is taken out of the clothes dryer, or when clothing is removed when the relative humidity is low. Clothing layers will develop an opposite charge as they rub against each other. When the layers are separated, one will retain its positive charge and the other its negative charge. If these charges are great enough, sparks will fly from one layer to the other. Charged clothing can induce a charge on the body. In a dry Canadian winter, we all know about the shock received from the car door after getting out of the car. As we slide across the car seat to get out of the car, a charge is built up on our clothing which then induces a charge on our body. When we reach for the metal door, the electric field near the finger tips exceeds the breakdown value and electrons flow as a spark to or from the frame of the car to neutralize the induced charge on the body. The same thing happens when we walk across a carpet and a charge is induced on the body. Just before one touches something of a lower potential, electrons jump to or from the body with the resultant spark. When charged clothing is removed, the body is no longer electrically neutral. A second spark can now occur when a metal object is touched.

These events tend not to occur at high humidities because textile materials pick up moisture from the atmosphere and become good conductors of electricity. Thus, when areas of two fabrics rub together, the areas of separated charge are in electrical contact and electrons flow to neutralize static charges.

Footwear can have a great effect on the dissipation of static charge from the body. If one is wearing insulated footwear, the electricity cannot pass from the body to the ground. As a result, any electric charge which is built upon the body stays on there, and under the proper conditions, is dissipated with sparks.

The major concern with static electricity is its discharging into an atmosphere which contains flammable vapours or gases to cause an explosion and subsequent fire. High electric fields can also be hazardous to electronic equipment.

4.0 MODIFYING FIBRES TO REDUCE ELECTRICAL CHARGE

In order to reduce electrical charge in clothing and its induced charge on the body, it is necessary to make the fibres as conductive as possible. There are several ways to do this. One is to apply an antistatic agent to the fibre surface, a second is to disperse conducting or antistatic particles within the fibre (2) and a third is to incorporate metallic or highly conductive fibres into the yarns. Wilson (3) considers the last method to be the best because, as well as providing a conducting path along which the charge is dissipated, the conducting fibres partially neutralize the charge on the fabric by corona discharge.

4.1 Antistatic Finishes

The majority of chemical antistatic agents work by attracting moisture to the fibre surface and so increase the fibre's conductive properties. Recently, polymer grafting techniques have used high energy radiation or chemical techniques to graft ionic functional groups to polyester or polyamide fibres to give improved and permanent moisture regain properties.

4.2 Particles in the Fibre

Another method of making fibres conducting is to embed fine particles of carbon black into polyester fibres which have been modified to have lower melting point surfaces. These are called "carbon epitropic fibres". About 2% carbon black by mass is needed in 100% polyester fabrics to give optimum anti-static properties. Epitropic carbon fabrics cannot be readily blended with cotton or polyester/cotton blends and the alkaline dye-bath of vat dyes seriously affects epitropic fibres. Carbon has also been used either as the core of a fibre or dispersed throughout the fibre during the spinning process.

4.3 Metal Fibres

The metal used for conducting fibres is extruded chromo-nickel stainless-steel filaments with diameters of 8 to 12 microns. These can be chopped into short staple lengths and blended during the drafting process with staple nylon, polyester/cotton or nomex yarns. The metallic fibres conduct high static charges from the surrounding fabric and generate extremely high electrostatic fields at the fibre ends. The air in the vicinity of these fibres becomes ionised and the charge leaks away as a corona discharge. To ensure that there is not a continuous conducting path along the whole surface of the fabric, less than 0.5 % to 5% metal fibres by mass are used.

4.4 Limitations of Antistatic, Metallic and Carbon Epitropic Fibres

Most antistatic finishes are not permanent and tend to wash off during laundering. Like textile fibres, they do not retain moisture at very low humidities and so are ineffective under such conditions (1).

Metallic and carbon epitropic fibres produce visible dark flecks in light coloured materials so this limits their use to coloured and/or functional apparel. Their efficiency is not high, having the equivalent to an increase of external humidity of about 15%. Both have higher resistivity values after laundering due to loss of fibres, poisoning or damage by the anionic detergent. In Scott's literature review (4), he states that Wilson found epitropic carbon fibres in 100% polyester to be more efficient in lowering the electrostatic body voltages in workwear than stainless steel in polyester cotton fabric.

5.0 LABORATORY TEST METHODS

Investigations in the field of static electricity have led to three main types of measurements. One is to measure the surface resistivity (to voltage) of textile materials, the second is to measure the charge built up on a person or the electrical capacitance of a body, and the third is to measure the energy required to ignite flammable vapours and gases. Either the measurements of surface resistivities or the voltages built up on the body is related to the ignition energy values of the flammable gases so that maximum standards of resistivity for textile materials or clothing can be set.

5.1 Test Methods Using Fabric Specimens

The current test methods have not been entirely satisfactory. The ASTM "Standard Test Method for Electrostatic Propensity of Textiles" D4238-83 measures the charge induced onto a rotating specimen by a direct current voltage and its subsequent rate of decay. This test method is recommended for the prediction of the electrostatic propensity of textiles and intra-laboratory work. However, the Test Method states that inter-laboratory precision for the method has not been established. The American Association of Textile Chemists and Colorists method relating directly to static electricity is AATCC Test Method 76-1987 "Electrical Resistivity of Fabrics" in which the surface electrical resistivity is determined

by means of an electrical resistance meter. This method says that "electrical resistivity influences the accumulation of electrostatic charge of a fabric" and recommends measurements be done at various humidities because the "accumulation of static electricity generally is greater the lower the relative humidity".

Research (4) has shown that methods which measure the resistivity of fabrics are inadequate as a means of testing the effectiveness of chemical anti-static finishes and that the body voltage or charge measurements are essential to check real effects of these additives. The surface resistivity values of fabrics with metal incorporated in them are influenced by the bridging effect of steel fibres under the electrode, thus low resistivities are measured and are not meaningful in terms of static protection. Wilson (4) examined the effect of anionic, cationic and nonionic surface-active agents on the electrostatic properties of natural, synthetic and blended fibre fabrics and picked the compound that was most effective at humidities lower than 40%. He found that treated material usually gave considerably lower voltages than untreated materials. However, in some cases, higher voltages were obtained after treatment even though the surface resistivities were considerably lower. Wilson explained this by the fact that there are a larger number of ions present on treated fabrics which greatly increase the initial charge on the treated fabric relative to an untreated fabric. Wilson (3) suggests that such finishes are best on underwear which is worn next to the skin where the humidity is not low.

Japanese researchers (5) claim to have gotten around this problem with their "KB System" which measures the frictional charge built up on fabrics and the subsequent decay curves. They show that their methods can be used with all types of antistatic finishes and modified fibres and has higher accuracy, reproducibility and lower variation than two other Japanese standard test methods, the Rotary Static Tester and the Faraday Cage method which uses fabric samples.

Hammant et al (6) describe an apparatus which can measure charge build-up either due to rubbing or to separation. They show how this method can be used successfully on various fabrics, including those with metal fibres.

Seasholtz (7) has suggested modifying commercially-available instruments and/or test methods so that meaningful results can be obtained with conductive fibres. As do the Japanese, she measures the electrostatic charge decay rate. She also gives a method to measure the electrical suppression when conductive fibres are placed in a fabric and a method to determine the charge generated when it is rubbed (triboelectric charge generation). She had yet to carry out experiments to determine the reproducibility of these methods.

5.2 Test Methods Using Clothed Persons

There is no standard method for measuring the static charge built up on a person. The generally accepted method is for a person to walk in a controlled fashion on a controlled surface into a Faraday cage. This is a wire cage onto which is induced an equal but opposite charge to that on the person entering it. This induced charge is recorded to give a measure of the static electricity on the person. Phillips (8) has proposed a standard calibration for a Faraday cage and a proposed methodology for using it.

5.3 Ignition Energy of Flammable Gases

There is no standard method to measure the energy required to ignite flammable gases. Typically, a known mixture of gas and air is placed in a grounded plexiglass box which contains an electrode. A charge is discharged through the electrode, either from a charged person or from a capacitor. The charge is increased until ignition occurs. Wilson (9) has shown that the critical voltage at which ignition occurs decreases with the reduction in size of the electrode down to 1 mm and then increases again with the smallest electrode because of corona discharging and that the lowest voltage for an ignition is independent of body capacitance. He concludes that the single parameter on which ignition depends is body voltage not the charge energy on the body.

5.4 Other Methods

There are test methods for measuring static in yarns, for fabrics that cling, such as those used in women's slips, and for footwear. They are not included here as they are not directly relevant to this review.

The April 1991 copy of the Textile Chemist and Colorist gives a status report on test methods for Static Electricity. The AATCC Test Method 134, Electrostatic Propensity of Carpets, has been revised to address control carpets, standard footwear and methods to improve data accuracy within testing facilities as well as different testing facilities. Dupont Canada has supplied the control carpets. Time is now being spent on the work of two sub-committees, one on electrical resistance and static decay and one on charge retention. (The former is chaired by Owen Bird from BASF Fibers in Arnprior.)

6.0 RESEARCH RESULTS

Scott at Stores and Clothing Research and Development Establishment at Colchester has written several reviews of Static Electricity in Clothing and Textiles, including the work done under contract with Wilson at the British Textile Technology Group (formerly the Shirley Institute). His review (4) of the build up of static on clothed persons shows that the greatest charge is generated when clothes are removed, when clothing brushes against adjacent layers, when clothes are removed quickly, when the subject is running, when footwear is worn and when the humidity is low. The wearing of footwear classed as anti-static or conducting was shown to reduce the developed charges significantly.

Further, van Savage (10) found that electrostatic voltages were negligible when Nomex (with 1% metal fibers) garments and flameproof cotton garments were worn with conductive shoes and the floor was grounded. Greater charges are generated at lower humidities when the test conditions included insulated shoes and/or an insulated floor.

Wilson (11) states that a localized charge on the cotton sleeve on a person can cause an ignition due to the fact that the intervening layers of clothing of a highly resistive material could allow a difference of potential of several hundred volts to build up.

Scott (4) notes that the majority of the work on the incendivity* of spark discharges from the human body has concentrated on surface resistivities of fabrics and the voltages generated on the body. It has been found that the capacitance of

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*Propensity to ignite.

the human body varies according to size, the footwear being worn and stance. Larger bodies have increased capacitance, insulated footwear raises the electrical insulation of the body and lowers the body capacitance. Raising one foot off the ground can lower the body capacitance by 40%.

Overall, the actual spark energy needed in real situations to ignite sensitive flammable vapour/air mixtures can be anywhere from 60 to 110 times higher than the published theoretical minimum values of ignition energies (11). Wilson (10) found that this higher energy is required because the discharge from the body is not all at once, but rather fragmented into discrete sparks and that because of the resistance of the body, part of the energy is absorbed as heat.

Wilson (4) also found that the fabrics which were most susceptible to static charges were cotton at low humidities and coated nylons over a wide range of humidities. For the fabrics he tested, he found that the simplest and most reliable parameter was surface resistivity and set the maximum value at 3×10^{11} ohm/square. (Note: the resistivity is the same no matter what the unit of area.) This coincides with the minimum energy of 12.3 mJ of charge on the body to ignite a fuel-vapour/air mixture whose minimum ignition energy is 0.2 mJ.

Henry (12) also concluded that simple resistivity tests on "homogeneous" fabrics can offer a reasonable guide to safety, the proposed limiting resistivity being 10^{11} ohms between opposite edges of a square sample. However, he found that this is not true of coated fabrics for which he recommended that some other form of test be devised. He also found that a Terylene/cotton blend can behave like a coated fabrics after a year's wear in use owing to the disappearance of cotton fibres from the surface.

7.0 VOLTAGE MEASUREMENTS ON CLOTHED HUMAN BODIES

In this area, most research has been carried out in the United Kingdom, the United States and in Canada. The general conclusions are that the static propensity of clothing and textiles depend on such factors as temperature, humidity, the type of textile the type of contacting or rubbing surface and the nature of the footwear worn. The general measurements of the polarization and magnitude of the charges developed between different materials agree quite closely with the rankings in the published triboelectric series.

The highest body charges were recorded at Arctic temperatures of -30°C and the lowest body charges in hot humid conditions. Cotton, polyester/cotton and polyurethane-coated nylon clothing caused the highest body charges at the lowest temperatures. Cotton, modacrylic and various polymeric-coated nylon clothing caused the highest body charges at lowest humidities.

Seat covers, made of PVC coated cotton or leather, in military vehicles tend to induce the highest body charges when a clothed subject slid off them.

De Santis and Hickey (13) measured the electrostatic build up on the Extended Cold Wet Clothing System (ECWCS) before and after laundering. They measured the potential accumulated with a Faraday cage enclosing a test participant wearing various ECWCS items. The donning and doffing took place outside the cage at a test temperature of -40°C. There was no significant change in potential after the uniforms were laundered. The authors concluded that the donning and doffing of the outer Gortex jacket created very little static electricity. The polyester pile shirt did show evidence of static electricity which resulted from the shirt brushing against a static-generating material. The static charge could be dissipated by grounding. It was recommended that personnel working with volatile liquids or explosives follow standard operating procedures before handling hazardous substances.

Hires and Dunn (14) evaluated a United States aircrew battledress uniform (ABDU) using the criteria that its static electricity resistance be minimal and as good as the current flight suit. The electrostatic charge accumulation was measured for the two garments while they were worn by personnel at 24°C and at 20, 40 and 65% R.H. and at 4°C with uncontrolled humidity. They found that no electrostatic build-up could be measured for either garment at 24°C and 65% R.H. No instances of sparking or shock generation was reported after 40,000 hours of wear. Subjective data confirmed the electrostatic test data (15).

8.0 IS STATIC ELECTRICITY REALLY DANGEROUS?

It has been hypothesized that sparks from static electricity can ignite various gas mixtures and cause explosions and subsequent injury or death. This certainly was the case when an explosion in an oxygen-enriched atmosphere killed 3 American astronauts. However, proof on a day-to-day level has been hard to document.

Scott (4) has delineated the operations which are most likely to pose a threat as rapid refuelling of aircraft or land vehicles with aviation fuel, handling explosive ordnance which is initiated by an electrical pulse, filling and deployment of hydrogen balloons for meteorological or other military purposes and use of highly flammable anaesthetics such as ether and cyclopropane in emergency field hospitals where modern "safe" anaesthetics may not be available. Finally, the successful deployment of modern nylon parachute canopies can be affected by static electrical charges which can be caused by the twisting of the lines during the opening process. (It should be noted that static electricity can also be generated by the flow of a fluid through a pipe, so that clothing-generated static is not the sole source of static electricity when refuelling aircraft or during the filling of hydrogen balloons.)

Scott notes that in Britain, the whole subject of fire caused by static electricity is shrouded by hearsay and circumstantial evidence and it is difficult to find many official reports which will confirm categorically that clothing or textiles caused accidental fires. Scott can only cite five such incidents after extensive enquiries made of various ministries and associations, both in Britain and abroad.

Scott describes them as follows:

"a. A bottle of di-ethyl ether was dropped and broken. The vapour was ignited by a spark from the underclothing and stockings worn by the person cleaning up the fluid. This incident occurred in the first-aid station of a tool manufacturer in 1952 and three women were injured.

b. An operator was returning petroleum spirit to a tank through a funnel when a static spark from the person to the metal funnel caused a fire. The fact that the victim was wearing rubber shoes was thought to have exacerbated the problem, by preventing body discharge dissipating away through the ground.

c. The US Air Force Aeromedical Laboratory has reported that in 1962 a fire was caused by an electrostatic discharge, when a person wearing a nylon outer garment in the Arctic touched an open gasoline can prior to refuelling a vehicle.

d. A technician wearing a cotton laboratory coat over a long-sleeved acrylic fibre jumper (sweater) ignited a small quantity of an explosive initiator compound on a laboratory bench. The relative movement and separation of the two textile materials at opposite ends of the tribo-electric series is considered to have generated a charge of sufficient energy to ignite the explosive material.

e. The US Navy Safety Centre recounted an incident in 1972 at NAS Glenview, Illinois, which attributes the ignition of gasoline-soaked underwear, being removed by a mechanic, to a static electrical discharge. The ignition occurred during removal of a cotton thermal underwear vest under quite moderate ambient conditions of 5°C and 37% RH. The only conductor in the vicinity was the concrete floor on which the victim was standing. Nevertheless an ignition did occur, the mechanic was burned, and for lack of any other evidence static discharge from the body was given as the cause of the accident."

Scott concludes that despite the sparse evidence, the "worst-case" philosophy has been adopted and thus anti-static precautions will continue to be mandatory. The precautions he outlines are given at the end of this paper.

In the 1960s, in response to a "number of incidents in the Department of National Defence which, because of no other apparent reason, were thought to be due to the discharge of static electricity", a Working Party on Static Electricity was set up by the Defence Research Board Advisory Committee on Clothing and General Stores (16). They visited CFB Rivers and CFB Shilo which have the climatic conditions (namely low humidity indoors) and tasks such as fuelling operations, ammunition handling and parachute packing which are conducive to such incidents. It was concluded that apart from a neoprene coated nylon jacket and trousers, none of the clothing worn at the bases created an electrostatic problem. It was recommended that "personnel employed on operations likely to present electrostatic problems should be made more positively aware of the danger involved by removing a garment and if necessary, regulations prohibiting the act should be enforced" (17).

In 1970, the committee (16) was asked to investigate a complaint from a Canadian Forces base that two technicians who were handling explosives had received shocks from static electricity when they slid off metal stools, one with a wooden seat and the other with a vinyl seat. They were wearing cotton outer garments. There is no documentation of the committee's final conclusion. However, the military had removed the vinyl-covered stools at the time of the incident, grounded the stools and rebriefed personnel on grounding themselves before touching explosive components.

There is no evidence of any CF personnel being hurt or killed by explosions caused by static electricity.

9.0 A STATIC ELECTRICITY SAFETY CODE

Wilson (4) has proposed a static electricity safety code, the main precautions being to always observe the correct grounding procedures, to wear anti-static footwear in conjunction with anti-static clothing and to make sure resistivity of footwear is monitored regularly as it can change with wear. Other points he makes are:

a. The highest static charges occur on clothing made from polyurethane-coated nylon outer garments and on clothing made from cotton, polyester/cotton and modacrylic fibres which have not been treated with an antistatic finish,

b. It is wrong to assume that cotton or rayon fabrics are always electrostatically safe. At low temperatures and in arid, frosty conditions, cotton is worse than many other fibres, particularly when it is separated from nylon.

c. It is best to avoid certain combinations of textile materials, for instance, the worst are nylon, wool or cotton in combination with acrylic fibres or PVC materials,

d. Anti-static chemical treatments for textiles, including fabric conditioners used in domestic laundering, may reduce the static charge on garments, but not always.

e. Certain combinations of finish and fibre may actually INCREASE the risk of incendive sparks occurring.

f. Do not remove outer clothing rapidly in a hazard area and keep both feet firmly on the ground.

g. Certain, uninsulated metal tools or rod-like fittings of diameters less than 1 mm can act as conductors to which or from which incendive sparks can be discharged from the body.

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This paper explains what static electricity is and how fibres can be modified to reduce their electrical charge. It describes the various test methods used in the study of static electricity and the research results of various authors. It cites various incidents attributed to static electricity and concludes with a static electricity safety code.

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Static Electricity
Antistatic Agents
Electrical Measurement
Electrical Properties
Electrical Discharge